METHOD AND INSTALLATION FOR MEASURING AND REGULATING THE FLOW RATE OF A LIQUID METAL IN A CONTINUOUS CASTING INGOT MOULD

The present invention relates to metallurgic installations and, more specifically, to installations of continuous casting of a liquid metal in an ingot mould.

Fig. 1 very schematically and partially shows in a
5 perspective view, the inlet section of a continuous metallurgic casting ingot mould 1. The ingot mould essentially includes a mould 2, open at its two ends in the case of a continuous casting. The liquid metal is brought into the ingot mould by an immersed nozzle 3, plunged into the mould 2. Nozzle 3 has
10 lateral ports 4 which aim at giving a horizontal component to the speed of the liquid metal at the outlet of nozzle 3.

Fig. 2 is a simplified cross-section view of a conventional ingot mould 1 illustrating, with arrows, the motions of the liquid metal in the inlet section of mould 2. As illustrated
15 in Fig. 2, the horizontal component of the liquid metal speed, given by ports 4 of nozzle 3, limits the vertical penetration depth of the metal supply stream into mould 2. Liquid metal $\underline{1}$ comes, for example, from a crucible 5 (for example, of blast furnace type). In the example shown in Fig. 2, crucible 5
20 includes, in its lower portion, an opening 6 associated with a controllable closing means 7 for controlling the liquid metal poured into nozzle 3. In conventional installations, the speed

of the liquid metal at the outlet of nozzle 3 can reach several meters per second. It is thus important to be able to control the liquid metal penetration in the cast. Indeed, too large a penetration of this liquid metal raises several problems. Among

5   these, the dragging of non-metallic particles coming from the powder or skin (not shown) which covers ingot 8 cast in mould 2 should be noted. These particles are trapped in the obtained metal. Too large a penetration of the liquid metal also causes an inverted thermal gradient since the hot liquid metal has an

10   effect upon the deep regions of the cast and causes, in particular, a local remelting deep into the at least partially solidified ingot, which also adversely affects the quality of the product.

To limit the liquid metal speed, braking systems and,

15   in particular, electromagnetic brake systems, are used.

A first type of electromagnetic brake uses a D.C. magnetic field in a direction perpendicular to the metal flow, which generates induced currents. The induced currents interact with the applied magnetic field and generate an electromagnetic

20   force which is a braking force aiming at nullifying the speed having caused the induced currents. Such D.C. magnetic field systems are generally formed of an electro-magnet totally or partially surrounding the ingot mould, and which generates a magnetic field transversal to the liquid metal. Such systems

25   have the disadvantage of being passive, that is, the magnetic field has a geometry and a position which are set once and for all, whereby any divergence at a given operating point reduces the braking efficiency. Accordingly, this braking appears to be inefficient when the supply conditions (speed, nozzle shape,

30   nozzle port immersion depth, etc.) change.

A second category of so-called sliding field electro-magnetic brakes uses an A.C. magnetic field generated by a polyphase power supply applied to inductors exhibiting an adapted space distribution. The magnetic field is thus given a

35   rotation or translation motion according to whether the inductor

shape is cylindrical or planar. Such magnetic fields enable accelerating or slowing down the liquid metal flow in continuous metallurgic castings. Thus, the system is active since the mechanical effect induced in the liquid metal is independent

5   from the liquid speed and is controlled by the operator.

The present invention more specifically relates to continuous casting installations equipped with a sliding magnetic field electromagnetic brake system.

In practice, in industrial continuous metallurgic

10 casting installations, a sliding magnetic field brake is formed of four sliding field inductors associated by pairs on each side of mould 2 of the ingot mould. In Fig. 1, two of these inductors have been schematically illustrated and designated with reference 9. In Fig. 2, the two inductors have been illustrated

15 in dotted lines. On a same side of the ingot mould, the two inductors are, as illustrated in Fig. 1, symmetrically arranged with respect to the axis of nozzle 3 on either side thereof to balance the metal distribution.

An example of an electromagnetic brake in a

20 metallurgic casting installation is described, for example, in European patent application N°0,550,785, the content of which is incorporated herein by reference.

A problem posed is that the geometry of ports 4 of nozzle 3 varies along time, in particular, due to an erosion of

25 these ports due to the fast flow of the liquid steel in the nozzle. This erosion does not necessarily evolve symmetrically, which then results in a hydrodynamic dissymmetry in the ingot mould due to a stronger flow on one side of nozzle 3 than on the other. Such an imbalance adversely affects the quality of the

30 finished product, since it results, not only in the introduction of non-metallic particles coming from the liquid metal skin, but also in different solidification durations from one side of the formed ingot to the other.

It is thus desirable to be able to differentiate the actions of sliding magnetic field inductors 9 to restore a balanced injection in the ingot mould.

For this purpose, it could be thought to separately supply the four inductors to provide many combinations in the organization of the liquid metal motions. In particular, the braking of the liquid metal flow on one side or the other of nozzle 3 could then be individualized.

However, the theoretical individualizing of the effects of the different inductors on the metal cast poses implementation problems due, in particular, to the need to then know the actual speed of the metal cast at a given time. Further, the current metal injection speed must be known on either side of nozzle 3.

A conventional method to adjust the sliding electromagnetic field in an ingot mould of the type illustrated in Figs. 1 and 2 consists of modeling the flow in a test structure using, for example, water to determine the excitation frequency of the inductors. Such a method is described, in particular, in above-mentioned European patent application N°0,550,785.

Clearly, such a method cannot enable knowing in real time the speed of the flow through both ports 4 of nozzle 3 and, more specifically, detecting an imbalance in this flow.

A first solution to know this speed would be to use stress gauges attached to rods dipped into the liquid steel of the ingot mould. By measuring a signal linked to the hydrodynamic effort exerted by the liquid steel on the rods, any flow dissymmetry can be detected and, accordingly, corrected by modifying the power injected in inductors 9. However, the use of rods, for example, alumina rods, poses several problems.

A first problem is that such rods form an intrusive element in the ingot mould which is likely to introduce pollution in the obtained product, in particular, by an erosion of the rods due to the liquid metal cast.

Another disadvantage is that the wearing by erosion of these measurement rods makes this solution, in practice, hardly viable from an economical point of view, due to the high consumption of alumina rods in an industrial process.

5   The present invention aims at overcoming the disadvantages of conventional continuous metallurgic casting installations. The present invention more specifically aims at enabling individualized control of the inductors of a sliding field electromagnetic brake of such an installation.

10   The present invention also aims at providing a solution which causes no pollution of the liquid metal during casting.

The present invention also aims at providing a solution which is particularly economical and requires no consumable

15 material replacement.

The present invention further aims at providing a solution which is particularly adapted to an individualized control of the powers injected into the inductors generating the sliding magnetic field.

20   To achieve these objects, the present invention provides a method for measuring the flow speed of a liquid molten metal in an ingot mould equipped with a sliding field electromagnetic brake, consisting of measuring the voltage or the current of at least one power source of the electromagnetic

25 brake and extracting the flow speed from this measurement.

According to an embodiment of the present invention, the method is applied to an electromagnetic brake, at least one inductor of which includes two batches of several conductors in a vertical direction, and consists of applying, for each

30 conductor, the following relation:

$$gradV = -i(\omega - vk)A - \rho j,$$

where ω represents the A.C. excitation pulse of the sliding field, $\underline{v}$ represents the metal speed, $\underline{k}$ represents the wave number of the inductive sliding magnetic field, A represents the

35 vector potential, ρ represents the resistivity of the metal, j

represents the density of the excitation current of the conductor, and V represents the voltage across the inductor.

According to an embodiment of the present invention, the speed measurement is used to servocontrol the excitation of the inductors onto a predetermined value.

The present invention also provides a method for regulating the continuous casting speed of a molten metal in an ingot mould, consisting of controlling the voltage or the current of at least one supply source of a sliding field electromagnetic brake including several inductors, with a measurement of the current or of the voltage in each inductor.

The present invention also provides a continuous casting installation of the type using a sliding field electromagnetic brake to control the flow of a liquid metal provided by two ports of a nozzle, characterized in that each inductor of the electromagnetic brake is powered by an individual circuit; and in that the installation includes means for regulating the supply voltage or current of each inductor to maintain the liquid metal flow speeds balanced between the two ports.

According to an embodiment of the present invention, each supply circuit of each inductor includes its own means for regulating the electromagnetic excitation power of this inductor.

According to an embodiment of the present invention, the installation includes a central station for controlling the supply circuits of the different inductors to regulate the liquid metal flow speed.

The foregoing objects, features and advantages of the present invention will be discussed in detail in the following non-limiting description of specific embodiments in connection with the accompanying drawings, among which:

Figs. 1 and 2, previously described, show an example of a continuous metallurgic cast installation of the type to which the present invention applies;

Fig. 3 very schematically shows the respective positions of the inductors in a continuous casting system to which the present invention applies;

Fig. 4 is a top view of an ingot mould equipped with a
5   casting speed control system according to the present invention; and

Fig. 5 schematically shows an embodiment of a circuit for controlling an inductor according to the present invention.

The same elements have been designated with the same
10 references in the different drawings. For clarity, only those elements which are necessary to the understanding of the present invention have been shown in the drawings and will be described hereafter. Reference can be made to literature, in particular, to European patent application N°0,550,785, for the forming of a
15 continuous casting installation with an active sliding field electromagnetic brake, since the present invention does not modify the structure of conventional installations.

A feature of the present invention is to take advantage of an individual power supply of the different
20 inductors of a sliding field electromagnetic brake to extract, from the electric characteristics of this inductor supply, information concerning the flow speed of the liquid metal in the ingot mould.

According to the present invention, the fact that the
25 currents induced by the conductive liquid metal in the magnetic field created by the inductors depend, among others, on the liquid metal flow speed, is used. In particular, assuming that the system is stabilized for a metal speed corresponding to a permanent liquid metal flow state, any disturbance which causes
30 a variation in this speed translates as a variation in the impedance of the inductor(s) responsive to the corresponding induced current. Thus, according to the present invention, a constant power source, either in current, or in voltage, is used to supply the inductors, and the possible variation of the other
35 variable (voltage or current) is examined to deduce a variation

in the liquid metal flow speed. Further, due to the fact that the inductors are powered separately from one another this speed can be localized. This information may, in a preferred embodiment, be used as the feedback of a system of control of the power supply of the different inductors to control the metal flow speed with a point of equilibrium corresponding to a given speed reference, for example, calculated based on a modeling such as described in European patent application N°0,550,785.

Fig. 3 very schematically illustrates the position of four inductors in a continuous casting installation. For simplification, only inductors 9 and a parallelogram symbolizing liquid metal 1 between these inductors have been shown.

Conventionally, each inductor 9 is formed of several imbricate turns adapted to being respectively supplied by different phases. In the example of Fig. 3, a two-phase electromagnetic brake system has been assumed. Each inductor 9 thus includes two circuits, respectively 10 and 11, of conductive imbricate turns in a magnetic yoke 12 opposite to metal 1 with respect to plane x-z in which are inscribed conductive circuits 10 and 11. A first conductive circuit 11 corresponding to a first phase is formed of three packs of conductors 13, 14, 15. The number of conductors of the central pack 15 corresponds to twice the number of conductors of packs 13 and 14 which surround two packs 16, 17 of conductors of second circuit 10 intended to be supplied by the second phase of the two-phase power supply. To form the adapted ampere-turns, the conductor batches are directly connected by phase to one of their ends and, via the supply source (not shown in Fig. 3), to their other respective ends. Thus, in the example of Fig. 3 where the vertical axis z is in the cast direction and the horizontal axes x, y, are respectively in the largest direction of liquid metal 1 corresponding to the alignment of the ports (4, Fig. 1) of the injection nozzle and in the smallest direction of liquid metal 1, the conductor packs of the different inductors are in the vertical direction z. They are, for example, directly connected

by their respective lower ends. By the connection of the conductor packs, the turns are run through by a current which, in the vertical sections, is inverted according to whether conductors 13, 14, or 15 for first circuit 11, and 16 or 17 for

5   second circuit 10 are involved. To illustrate this flow in opposite directions, an example of current flow, symbolized by a "." or a "x" according to the flow direction in the vertical sections, has been indicated in Fig. 3.

The current flow as shown in Fig. 3 is conventional

10   and will not be detailed any further. It should only be noted that the present invention may be implemented in a system including a greater number of phases, for example, in a three-phase or polyphase system while respecting the usual phase imbrication to obtain a polyphase sliding field. It should also

15   be noted that, as illustrated by the representations of the current flow directions in Fig. 3, axis $\underline{x}$ corresponds to a longitudinal axis of symmetry which in fact is an axis of antisymmetry for inductors 9 which are opposite two by two.

In a sliding field electromagnetic field such as

20   illustrated by the preceding drawings, it can be considered that the potential vector A, the current density $\underline{j}$, and the electric field E have a single component along vertical axis $\underline{z}$, that the speed of induced metal $\underline{v}$ has a single component along longitudinal axis $\underline{x}$, and that the magnetic induction B has two

25   components along horizontal axes $\underline{x}$ and $\underline{y}$.

The synchronism speed v_s of the sliding electromagnetic field is equal to the product of the operating frequency $\underline{f}$ of the A.C. excitation of the two phases by the wavelength λ of the sliding field wave. It should be noted that

30   the actual speed $\underline{v}$ of the metal is opposite to this synchronism speed which also has one component only along longitudinal axis $\underline{x}$.

The equations which govern the operation of the elec-tromagnetic field, respectively in the inductor, in the air, in

35   the magnetic yoke, and in the induced metal, may be expressed as

follows in projection on vertical axis $\underline{z}$ where the single unknown value is component A along Oz of potential vector $\bar{A}$.

In the inductor, one may write:

$$-\operatorname{div}\left[\frac{1}{\mu_0}\left(\overrightarrow{\operatorname{grad}A}\right)\right] = J_i \, ,$$

5 where Ji represents the current density imposed in the inductor by the power supply, and where μ_0 represents the permeability of vacuum.

In the air, one may write:

$$-\operatorname{div}\left[\frac{1}{\mu_0}\left(\overrightarrow{\operatorname{grad}A}\right)\right] = 0 \, .$$

10 In the magnetic yoke, one may write:

$$-\operatorname{div}\left[\frac{1}{\mu_0\mu_r}\left(\overrightarrow{\operatorname{grad}A}\right)\right] = 0 \, ,$$

where μ_r is the relative permeability of the magnetic medium.

In the induced metal, on may write:

$$-\operatorname{div}\left[\frac{1}{\mu_0}\left(\overrightarrow{\operatorname{grad}A}\right)\right] = i\frac{\omega}{\rho}A\frac{v}{\rho}\frac{\partial A}{\partial x} \, ,$$

15 where ω represents the electric pulse of the A.C. power supply ($\omega = 2\pi f$) and where ρ represents the resistivity of the liquid metal.

As a first approximation, to neglect edge effects, it can be considered that the potential vector A is a sliding wave due to an infinitely long inductive sheet following longitudinal
20 direction $\underline{x}$. It can then be considered that the only component A of the vector potential according to vertical axis $\underline{z}$ can be written as:

$$A = A_0 e^{i(\omega t - kx)} \, ,$$

25 where $\underline{k}$ represents the wave number of the inductive sliding magnetic field ($k = 2\pi/\lambda$).

With this approximation, the preceding relation in the induced metal can be expressed in projection on the vertical axis as being equal to:

30 $$-\operatorname{div}\left[\frac{1}{\mu_0}(\overrightarrow{\operatorname{grad}A})\right] + \frac{i}{\rho}(\omega - vk)A = 0 \, .$$

Introducing the synchronism speed of the inductor in this equation provides:

$$-\text{div}\left[\frac{1}{\mu_0}(\overrightarrow{\text{grad}A})\right] + i\frac{2\pi}{\lambda\rho}(v_s - v)A = 0 \ .$$

All the above expressions show that the only variable quantities for a given current are potential A and speed $\underline{v}$ of the liquid metal.

It should be noted that, rather than the current, the current density must be set. However, the number of conductors per pack (that is, the number of turns) has no incidence since the voltage variation of each phase will be compared in a relative manner for a metal speed variation.

Voltage gradient gradV can thus be calculated based on the respective values of potential vector A, of imposed current density $\underline{j}$, and of the previously established relations.

By projecting on vertical axis $\underline{z}$ the following Maxwell equation:

$$\vec{j} = \sigma\left(-i\omega\vec{A} + \vec{v}\times\vec{B} - \overrightarrow{\text{grad}V}\right) = \sigma\left(-i\omega\vec{A} + \vec{v}\times\overrightarrow{\text{rot}A} - \overrightarrow{\text{grad}V}\right)$$

which links values $\underline{j}$, gradV and A, and by replacing $\vec{v}\times\overrightarrow{\text{rot}A}$ by ivkA, the following relation giving the voltage gradient on each conductor is obtained:

gradV = $-i(\omega-vk)A - \rho j$.

It is then sufficient to sum up the values obtained for all the conductors in each pack to obtain the total voltage of the respective phases. If need be, the impedance of each phase, rather than the voltage, may be deduced by dividing this voltage by the currents imposed by current sources 31 and 32.

As a specific example of implementation, taking for each conductor pack a rectangle of 160x100 mm^2 (except for end packs 13 and 14 which each correspond to a rectangle of 80x100 mm^2), the current density is 6.75x10^6 amperes rms per m^2. Assuming a relative permeability μ_r of 1,000, the wavelength λ of the sliding field is approximately 1.3 m. For an operating frequency of, for example, 0.65 Hz, the synchronism speed v_s is 84.5 cm/s.

Assuming, in a simplified manner, that the induced metal is a solid of constant resistivity $\rho = 100.10^{-8}$ Ωm (which corresponds to a conductivity of 1.10^6 $(\Omega m)^{-1}$, that is, substantially that of liquid steel), the respective values of the total voltage for the conductor packs may be calculated for two modules of liquid metal speed of 10 and 9 cm/s. For example, for batches 16 and 17 of 40 conductors having a square cross-section of 20x20 mm^2 in series, which amounts to considering batches of 40 spirals in each of which flows a current of 2700 A rms, voltages of 38.66 volts and 36.74 volts in modulus are obtained for, respectively, 10 cm/s and 9 cm/s. Accordingly, the modulus of the voltage of the corresponding phase decreases by approximately 2/38, that is, approximately 5%. On the impedance of the corresponding phase, the variation also is on the order of 5% for a same metal speed variation.

Accordingly, it can be considered that with industrial values, a variation on the order of 10% of the metal speed causes a variation on the order of from 5 to 6% in the voltage and in the impedance. This variation is substantial enough to be used to control the regulation circuits to bring the speed back to its mean reference value, or to bring down to zero an interval between two values.

Fig. 4 illustrates, in a top view of an ingot mould, the respective electric connections according to the present invention of the two-phase inductors illustrated in Fig. 3. The direct connections between the difference conductor packs, for example, in the lower portion of the system, have been symbolized by dotted lines.

In the top view of Fig. 4, nozzle 3 has been schematically at the center of mould 2. Each inductor 9 has been symbolized by its magnetic yoke 12 and its two conductive circuits 10, 11 formed, in the vertical direction, respectively of two packs 16, 17 of a same number of conductors and of three packs 13, 14, 15, the central pack 15 having a number of conductors which is twice that of end packs 13 and 14.

As indicated previously, sections 16 and 17 of each circuit 10 are directly connected, for example, by a cable 18 in their lower portion. Similarly, packs 13 and 14 are each connected to pack 15, for example, by cables, respectively 19

5   and 20. In the upper portion of the vertical conductive packs, said packs are connected by their ends to supply means. According to the present invention, conductive circuits 10 and 11 of each inductor 9 are individually connected to a supply circuit 21 specific to the concerned inductor. Thus, packs 13

10   and 14, pack 15, pack 16, and pack 17 are connected to a circuit 21 by respective cables 22, 23, 24, and 25.

According to the present invention, all circuits 21 have an identical structure which will be described hereafter in relation with Fig. 5. Each circuit is individually connected to

15   a central control station 26, for example, by cables 27. Cables 27 have been illustrated as including several independent conductors to bring, to each supply circuit 21, the different necessary A.C. supply phases as well as, if necessary, appropriate control signals provided by central station 26. It

20   should however be noted that only the control signals could be individualized and that the polyphase supply conductors could be common to the different circuits 21, said circuits then being in charge of adapting the respective powers to be provided to each of the inductors.

25   For clarity, the different references of inductors 9 have been indicated only once in Fig. 4, each inductor having a similar structure and differing from the others by the current flow direction only, as illustrated in Fig. 3.

Fig. 5 very schematically shows the structure of a

30   supply circuit 21 of an inductor according to the present invention.

In the example of Fig. 5, it is assumed that each inductor phase is supplied by a low-frequency A.C. signal, of which the rms current value is set to a predetermined value

35   according to the nominal braking characteristics desired for the

ingot mould. Thus, circuit 21 of Fig. 5 includes two current sources 31 and 32 supplying, for example, cables 23 and 25 respectively associated with conductor packs 15 and 16 as illustrated in relation with Fig. 4. Current sources 31 and 32

5   are, according to the present invention, controllable, respectively, by signals 33 and 34 provided by regulation circuits, respectively 35 and 36. Each circuit 35, 36, measures the voltage between, respectively, conductors 22 and 23 and conductors 24 and 25. These voltage measurements are intended to

10   evaluate the liquid metal speed opposite to the corresponding inductor.

In the embodiment illustrated in Fig. 5, each regulator 35, 36 receives a reference 37, 38 from the control station 26 (Fig. 4) and is in charge of controlling the current

15   provided by sources 31 and 32 to enable a regular and balanced speed in the ingot mould. However, the regulation may also be provided to be performed directly by central station 26, or a voltage regulation may be provided to be used to calculate the speed, so that it is exploited by the central station 26.

20   Of course, the inductors may also be supplied by a controllable voltage of predetermined value, and a current measurement, the variations of which will then depend on the speed, may be used, thus enabling feedback on the supply voltage source.

25   The practical implementation of the method according to the invention, by the forming of electronic circuits or the programming of computing tools necessary for the calculation, is within the abilities of those skilled in the art based on the functional indications given hereabove. It should be noted that

30   the complexity of this electronic circuit or of the programming computations will depend on the desired accuracy for the control, as for any conventional control.

An advantage of the present invention is that it enables measuring the liquid metal speed in the ingot mould

35   without any physical contact with the liquid metal.

Another advantage of the present invention is that it is particularly well adapted to a control of continuous casting systems since it is very easy to have a feedback on the current or the voltage in the inductors.

5 Another advantage of the present invention is that it requires no modification of conventional continuous casting installations with a sliding field electromagnetic brake, except for the control circuits of the different inductors.

Of course, the present invention is likely to have

10 various alterations, improvements and modifications which will readily occur to those skilled in the art. In particular, the adaptation of the method according to the number of phases of sliding field electromagnetic brake systems is within the abilities of those skilled in the art according to the application

15 and to the functional indications given hereabove. Further, the numerical values indicated in the foregoing description have been indicated only to show the industrial feasibility of the present invention and for illustration only. Further, it should be noted that the present invention may be implemented in any

20 continuous casting system, whatever the shape of the ingot mould, provided that it uses an active sliding field electromagnetic brake system.